

Article

Thermal Pollution Mitigation and Energy Harnessing of the Condensation Process of an Olive Oil Extraction Refinery: A Case Study

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Abstract: This paper presents a model to assess strategies for bettering a hexane condensation system from an olive oil extraction refinery in Portugal's mountainous north. The water used as a cooling fluid is discharged with a higher temperature than the mountain river, provoking the deterioration of the aquatic flora and fauna, leading to high environmental impact. The model allowed the comparison of solutions for different temperatures of discharge for summer and winter and possible heat recovery back to the factory. The current condensation system power is 1.838 MW and consists of a four-walled pond of 115.3 m³ that cools down the submerged hexane pipes. Nudging in the pond's structure leads to the introduction of internal channels to increase the turbulence, thus increasing the hexane–water heat exchange rate. Heat recovery of 19.38 kW is possible for the water coming from the pond in the drying bagasse process inside the factory, before discharge into the river. However, the model demonstrates that the decrease in temperature after the heat recovery process falls short of avoiding thermal pollution, leading to complementary actions such as shading the channel or changing the discharge velocity or angle to mitigate the thermal pollution locally.

Keywords: thermal pollution; energy efficiency; heat exchange



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1. Introduction

Olive oil extraction is a crucial economic sector in Portugal. In recent years, 130,000 small farmers produced approximately 600,000 tons of olives, with 12% harvested in the northern region of the country [1]. There was a need to modify the layout of the condensation system of an extraction olive oil refinery located in northern Portugal due to the high environmental impact related to the deterioration of a nearby river's aquatic life from the discharge of heated water from the factory's cooling system.

Figure 1 shows the study area, located in Mirandela municipality, in the northeast of Portugal. The olive oil extraction factory is next to the Tua river (≤ 100 m), one of the Douro river's main affluents. This river is born in the mountain, at 1000 m asl, at the Sabor river basin's head and ends in the Douro river. It is a cold-water river with high aquatic diversity and endemic species.

In this region, a mechanical wrenching precedes a chemical extraction of the oil. The first one relies on small independent producers or associated cooperatives distributed throughout the region that extract the oil through mechanical pressing processes. Those who extract the olive oil by pressing means will be named Mechanical Extraction Producers (MEP). The result of MEP is virgin oil of very high purity. The by-product obtained is olive bagasse with a high water content, which is very polluting due to a significant content of organic substances, including sugars, tannins, polyphenols, polyalcohols, pectins,

and lipids [2]. However, the MEP cannot extract the residual amount of olive oil from this by-product through pressing processes.

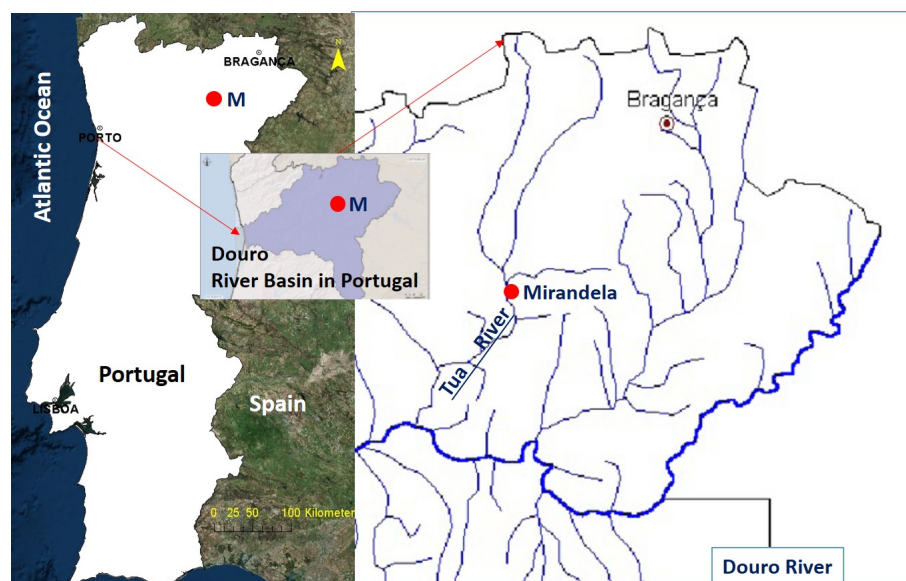


Figure 1. Portugal map: Terrain elevation map (0–1993 m asl) and main river basins, with location of olive oil extraction factory in Douro river basin (red dot).

The chemical extraction comes into play since MEP cannot treat their by-product. Therefore, the smaller producers sell it to regional factories, which extract the remaining oil with hexane used as organic solvent in the Chemical Extraction Factory (CEF) that extracts the remaining olive oil. The industrial waste that is the final bagasse is finally dried and used as biomass fuel to generate heat necessary in other processes within the CEF with a high heating value (HHV) of 22,868 kJ/kg [3,4]. In this way, the bagasse becomes a raw material of high energy value. The relationship between MEPs and CEF is crucial for the productivity of the olive oil sector in the region and the final disposal of the waste generated during the different processes. Figure 2 shows the flow chart of the olive oil extraction process.

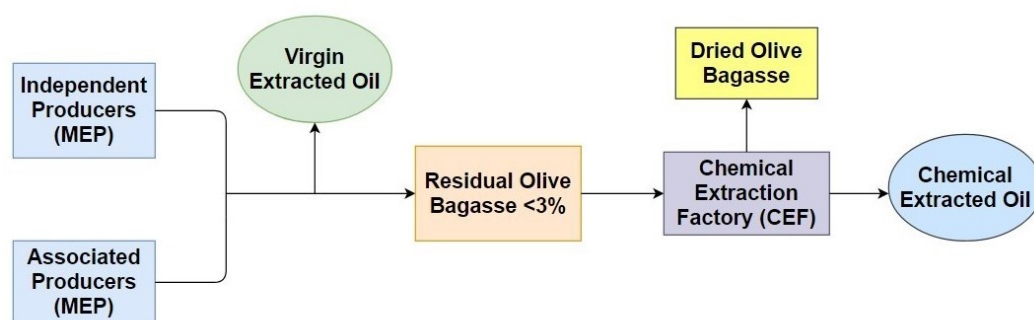


Figure 2. Relation between MEP and CEF.

The CEF has a series of technical operations with intense freshwater use for the chemical extraction process of olive oil, where each litre of olive oil requires 5–7 L of water [5]. The hexane condensation also requires large quantities of water, and the improper disposal of the cooling water of the hexane condenser is currently provoking a focus of thermal pollution into a nearby river, which has resulted in financial penalties. Modelling future technical strategies to mitigate thermal pollution and avoid waste by identifying energy harvesting opportunities are the focus of this work.

2. State of the Art

The river water that serves the hexane condensation returns to the water body at a higher temperature. The sudden change of temperature decreases the dissolved oxygen (DO) in the river, making an abrupt decrease in DO, thus killing aquatic flora and fauna by hypoxia [6,7]. The decreasing of the DO is approximately 33.1% in a range of temperature of 10 °C to 30 °C [8]. Other physical properties affected are density, viscosity, vapour pressure and gas diffusion. Moreover, an increase in the temperature will have a significant effect in chemical reactions; the rate reaction is doubled for each 10 °C rise [9]. The thermal pollution changes riverine ecology, affecting the metabolism of the living organism and the natural conditions of the habitat [10,11]. The thermal regime plays a key role in biological processes such as larval metamorphosis success, metabolic rate, and overall survival [12]. A great number of aquatic creatures facing this new situation cannot tolerate it, thus provoking the migration of populations and allowing the arrival of newer species, thus changing the ecosystem features [13]. This migration is called replacement fauna by Naylor (1965) [14], where some living organisms are pre-adapted to the peculiar new condition of the polluted area and become stronger than the native species.

The proposals to mitigate the thermal pollution in water bodies specifically adapted to this case can be analyzed from environmental and economic points of view:

Environmental: Issakhov, Alibek, and Zhandaulet in the simulation of thermal pollution zones [15] suggest changing the velocity and angle of discharge to the river since small values of these two parameters affect the smallest possible area in the river. Coutant et al. suggest the dilution of the heated water in cool water before entering the river [16]. Focusing in the discharge channel (factory-river), Abdi, T. Endreny, and D. Nowak simulated having an aquatic green structure in the shoreline, plant riparian vegetation of local trees, which will avoid an incidence of the solar radiation by the shade; this also avoids erosion and induces cooling groundwater inflow and hyporheic exchange [17]. Having a more extended channel will increase the dissipation of heat by natural convection and interfacial friction upper layer of water and surrounding air [18].

Economic: Firstly, to avoid the fines that entail the thermal pollution in the river by Portuguese environmental authorities, and secondly the cross-sector production proposed by ME Webber [19] using the heated water to produce power, or a thermal heat recovery system to profit off the heat in some processes within of the plant for a reduction of the discharge temperature and greater energy efficiency. The cooling water system is essential for the effective running of power stations or different kinds of industries, like the olive oil industry, and achieving a perfect equilibrium concerning the environment and the economy [20].

3. Description of the Problem

The bagasse arrives at the CEF with 3% of oil and is submitted to two stages: A physical separation (centrifugation) followed by a chemical one (decantation and distillation). Phase I, showed in Figure 3, enables the further extraction of 1% of residual oil by a centrifuging process followed by a moisture reduction from 65% to 55%. Phase II's chemical process starts when hexane is added to the bagasse to promote the olive oil separation, further recovered in a conventional distillation process. The hexane is recovered at the end of the circuit when it is condensed. That is the concrete source of the problems in this olive oil factory. One will further describe in this article the inefficiencies of the current cooling system.

The condensation of the hexane by cooling water does not occur in industrial condenser equipment but rather an unconventional condensation system consisting of a four brick wall pond filled with water from the Tua river. The pond houses a piping system where the hexane circulates and condenses, transferring the latent heat to the pond's water. The river then receives the discharged pond's warmed water.

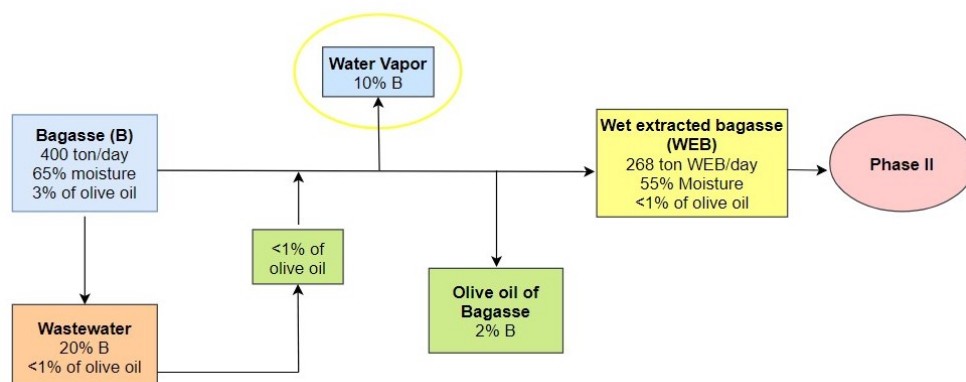


Figure 3. Phase I of dried bagasse.

Figure 4 shows that the water from the river is extracted in point 1 to condense the hexane that enters the cooling circuit in point 3 in vapour state and exits at point 4 in a liquid state.

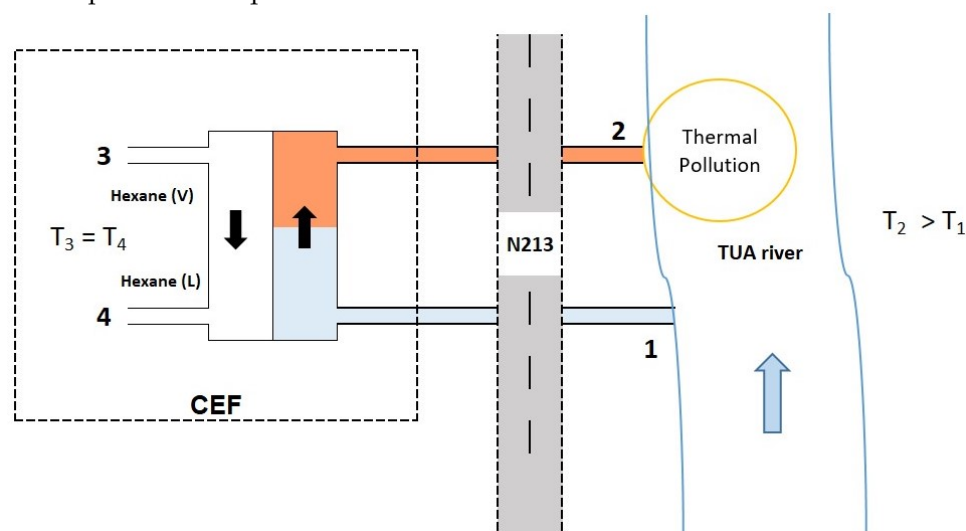


Figure 4. River–factory scheme. The distance between the river and the CEF is approximately 100 m and is mediated by national road N213.

The water and the hexane circuits are independent, and there is no mixing besides a simple heat-exchanging process where the water returns to the river in point 2, with a higher temperature, thus being a source of thermal pollution.

The main problems of the condensation process of hexane are environmental and economical: Heated discharges into a stream drastically alter the ecology of the water system [16], having an inefficient heat exchange process that fails to dissipate all the heat extracted from the hot hexane. Adopting an efficient condensation system that does not negatively impact the river can be achieved either by improving the condensation process or reducing local environmental effects. The improvement of the condensation process can be divided into two different solutions:

1. (a) Improving the condensation system by allowing recovered energy to be re-introduced into part of the Phase I drying bagasse process. The amount of water to be pumped and returned into the river depends on complex heat recovery models. One of the technical measures to be adopted in the condensation's improvement is to change the condenser operation, thus guaranteeing a continuous flow of water entering and leaving the condenser. Smart modifications to the layout of the condenser and pumping system can achieve this.

- (b) The second vector promotes the heat recovery from the condenser to further dry the olive bagasse from 65% to 55% of moisture, thus increasing the system's whole efficiency. The yellow circle in Figure 3 highlights the process of evaporation of the 10% moisture of the processed bagasse per day.
2. Reducing local environmental effects: This can be achieved by reducing the previous solution's discharge temperature.

The development of a solution based on the best environmental, technical, and economic trade-off for the recovery of the heated water's thermal energy will (1) decrease the environmental impact on the aquatic life of the river and (2) increase the eco-efficiency of the CEF.

4. Methodology

The modification of the pond's layout and the water mass determination model are the key factors addressed in solving this problem. These two subjects are the target of this section.

4.1. Modification of the Layout of the Pond

The hexane condensation process works by filling the pond with water from the Tua river; after that, the hexane is circulated through the pipe submerged in the pond's water. It is a very inefficient process since the lack of movement by the water causes the heat transfer to occur through a natural convection process, so the heat transfer rate is very low [21]. Instead, the process is executed through batches instead of continuously, thus yielding hexane losses in the vapour phase because it is not possible to condense all the hexane during these circumstances. Figure 5 shows the pond's current structure's aerial scheme. Point 1 is the inlet of hexane in the vapour state, and point 2 is the outlet in a liquid state. Point 3 is the pumping system that impels the water from the river into the pond.

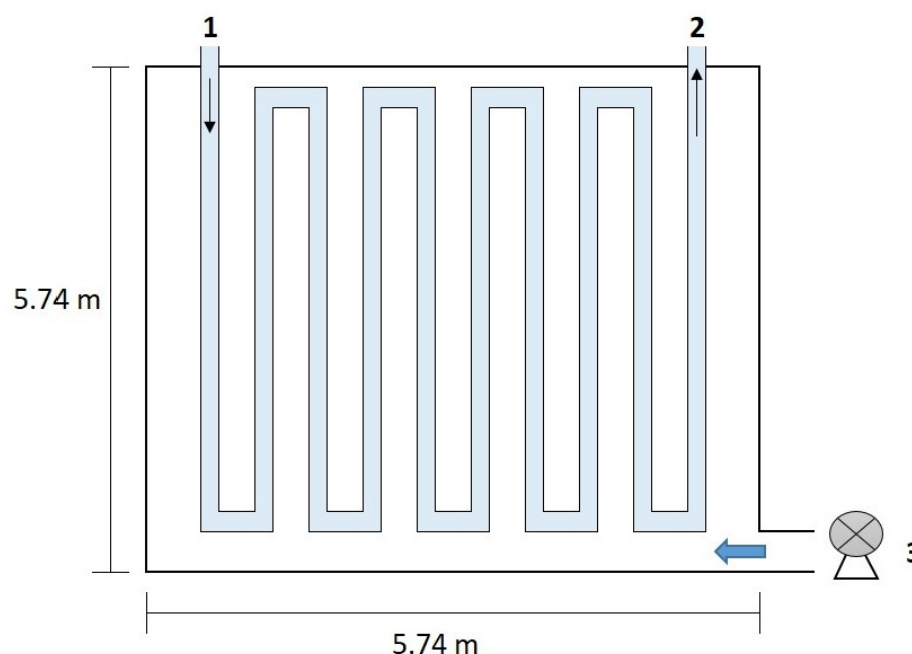


Figure 5. Scheme of the current pond.

The physical consideration to improve the heat exchange rate toward the water is to avoid its accumulation without movement in the pond, since the heat transfer from the hexane to the water is carried out by natural convection. The water particles that are close to the pipe walls gain heat, and due to differences in density they flow towards the top, causing that colder molecule to move downwards. The cycle occurs until reaching a temperature homogeneity throughout the fluid mass. It is a flawed process in terms of

achieving a higher rate of condensation of the hexane that flows through the pipe's interior. The increase in the velocity of the fluid causes an increase in turbulence; greater turbulence guarantees a greater heat exchange rate [21].

The turbulence of water inside the pond can be achieved by firstly operating the pond in a steady flow to constantly have water entering and leaving it [22], and secondly building internal channels that allow redirection of the water flow. The turbulence is required because larger heat transfer coefficients are obtained for larger Reynolds [21–23]. The Reynold's number to get a turbulent regime flow in an open channel has to be greater than 2000 and is evaluated through Equation (1)

$$Re = \frac{\dot{v}_w \rho_w}{(b + 2y) \mu_w} \quad (1)$$

where \dot{v}_w , ρ_w and μ_w are the volumetric flow, density and dynamic viscosity of the water, respectively; b is the width of the channel; and y is the height that the water reaches in the channel. Figure 6 shows the pond's aerial scheme, with the channels proposed and the hexane piping housed in it. Now, this whole set becomes the new improved heat exchanger.

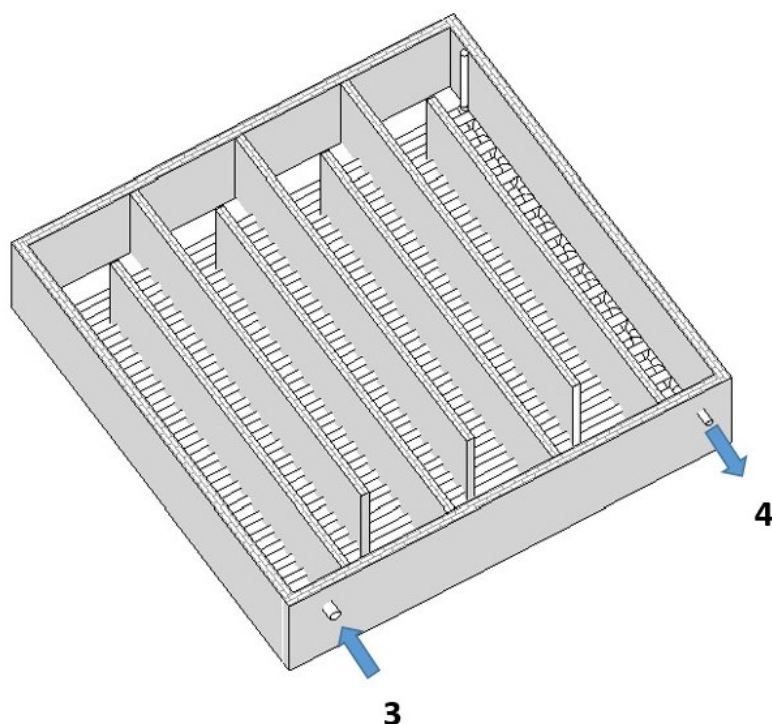


Figure 6. Pond with internal channel.

The pond guarantees high turbulence due to redirection, flow velocity, and the water's impact on the pipe and channels' walls after building the channels. The outlet at point 4 guarantees a steady water flow.

4.2. Water Flow Determination Model

One developed a specific model to evaluate how the water quantity is affected by other variables such as mass flow of hexane to condensate, season of the year in which the factory operates, and the total thermal energy in the bagasse dried process.

The hexane only needs to change phase without the need for sub-cooling. The amount of heat that the hexane will transfer to the water will be equivalent to the heat of condensation [21] that is given by Equation (2) where \dot{m}_h is the mass flow of hexane, and λ_h is the latent heat of hexane.

$$\dot{Q}_h = \dot{m}_h \lambda_h \quad (2)$$

Through an energy balance in the condensation system (pond-pipes) of Figure 5, the mass flow of water can be determined by Equation (3)

$$\dot{m}_w = \frac{\dot{m}_h \lambda_h}{C_{pw}(T_{fw} - T_{iw})} \quad (3)$$

The heat losses to the environment by heat convection and losses through the brick wall by conduction are neglected. The water will not change phase, and the heat absorption will increase the water temperature. Thus, in Equation (3), T_{fw} and T_{iw} are respectively outlet and inlet temperature of the water to the pond; C_{pw} is the specific heat of the water, which will remain constant in the range of temperature of the whole process [24].

When water leaves the pond for the heat transfer process to the bagasse stream, it needs to recur to do another energy balance for both streams, water of the pond, and bagasse according to Equation (4) to determine the final temperature of the water. The bagasse stream contains a high moisture level and because of that one can equal its properties to the same as the water stream, (bw).

$$T_{fe} = \frac{\dot{m}_w T_{i(fw)} + \dot{m}_{bw} T_{i(bw)}}{\dot{m}_{bw} + \dot{m}_w} \quad (4)$$

Moreover, from Equation (4), the outlet temperature of the pond assumes the initial temperature $T_{i(fw)}$ of the heat transfer process from the water to the bagasse stream.

5. Results and Discussion

The model allows testing the best solutions regarding the variation in water flow, the river's seasonal temperature variation, and energy savings by reintroducing the heat extracted from the hexane into the bagasse drying process. The results and discussion are addressed in Sections 5.1–5.3.

5.1. Mass Flow of Hexane to Condensate

The yield of olive oil chemical extraction varies according to the solvent to bagasse ratio as indicated in Figure 7.

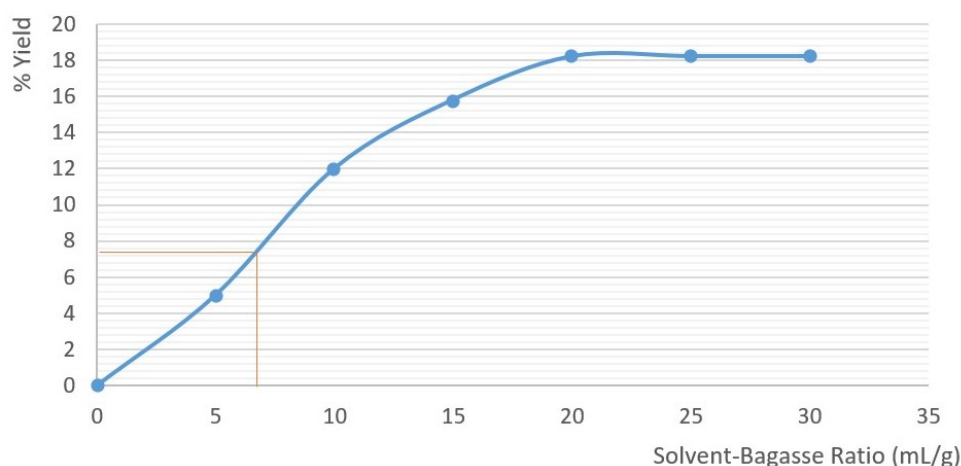


Figure 7. %Yield vs. hexane solvent–bagasse ratio.

The highest yield is 18% for a 20:1 ratio, but only when one adds extra chemicals to the mixture. For the current case, the olive oil yield will remain at 7.5% for a hexane/olive bagasse solvent ratio of 6.5 mL per 1 g [25].

The factory processes 1.39 kg/s of olive bagasse per day, and the hexane/bagasse mass ratio will be 4.01 assuming the hexane's density to be 616.00 kg/m³ [24]. The quantity of hexane required and how much latent heat is needed to transfer to the water is presented in Table 1.

Table 1. Heat of condensation of hexane.

Description	Symbol	Value	Units
Mass flow of olive bagasse	\dot{m}_b	1.39	kg/s
Density of hexane	ρ_h	616.00	kg/m ³
Hexane mass/bagasse mass ratio	m_h / m_b	4.01	kg/kg
Mass flow of hexane	\dot{m}_h	5.57	kg/s
Latent heat of condensation of hexane	λ_h	335.34	kJ/kg
Heat rate of condensation of hexane	\dot{Q}_h	1838.10	kW

5.2. Operating Season in the Year

The temperature of the mountain river water in the summer is approximately 18 °C, and in the winter, 10 °C. The temperature differences in winter and summer lead to the need to use seasonal specific water mass flows. The temperature differences are suggested between the discharged water and the river so that this difference affects the smallest possible area in the river. For winter, the difference should be 5 °C, and for summer it should be 3 °C [15].

5.3. Thermal Energy in the Bagasse Dried Process, Phase I

The water quantity evaporated to reduce the moisture from 65% to 55% during the bagasse drying of phase I is 0.463 kg/s. The amount of total heat necessary to evaporate this 10% of moisture (\dot{Q}_T) is composed of sensible heat (\dot{Q}_s) and evaporation latent heat (\dot{Q}_L). The water that comes from the pond will provide the heat that comes from the carried out condensation process. Table 2 describes the quantities of heat required to evaporate the water contained in the bagasse.

Table 2. Parameters required to evaporate the water of the bagasse stream.

Description	Symbol	Value	Units
Mass flow of water to evaporate	\dot{m}_w	0.463	kg/s
Specific heat of water	C_{pw}	4.186	kJ/kg °C
Initial temperature of the bagasse water	$T_{i(bw)}$	20	°C
Final temperature of the bagasse water	$T_{f(bw)}$	100	°C
Latent heat of vaporization of water	λ_w	2259.36	kJ/kg
Sensible heat required	\dot{Q}_s	155.04	kW
Latent heat required	\dot{Q}_L	1046.00	kW
Total heat required	\dot{Q}_T	1201.04	kW

5.4. Heat Recovery

5.4.1. Seasonal Water Flow Needs

According to Equation (3) the mass flow of water will be inversely proportional to the wanted outlet temperature and the inlet temperature, which will depend on the year's season. In Table 3 are described different values of mass flow water to different outlet temperatures for winter and summer, Figure 8.

The recommended discharge temperature values are 15 °C and 21 °C, respectively, for winter and summer; besides, the bagasse stream's temperature within the factory is 20 °C. Therefore, to get a thermal heat recovery, an adequate outlet temperature needs to be selected. However, by analyzing Equation (4), one concludes that the water flow to be evaporated is minimal when compared with the lowest values in Table 3; therefore, it can be considered negligible. Equation (5) shows that condition.

$$T_{fe} = \frac{\dot{m}_w T_{i(fw)}}{\dot{m}_w} \quad (5)$$

Thus, Equation (5) shows that any temperature value selected from Table 3 will remain constant after the heat recovery process. At this point, environmental considerations

are crucial because any value above the recommended value will harm the river's ecology, and any value below the recommended value would impede the heat's recovery, with additional pumping costs.

Table 3. Mass flow of water in winter and summer for different outlet temperatures.

Mass Flow of Water Winter	Mass Flow of Water Summer	Final Temperature of Outlet Water
\dot{m}_w (kg/s)	\dot{m}_w (kg/s)	T_{fw} (°C)
87.82	-	15
39.92	146.37	21
21.95	36.59	30
17.56	25.83	35
14.63	19.96	40

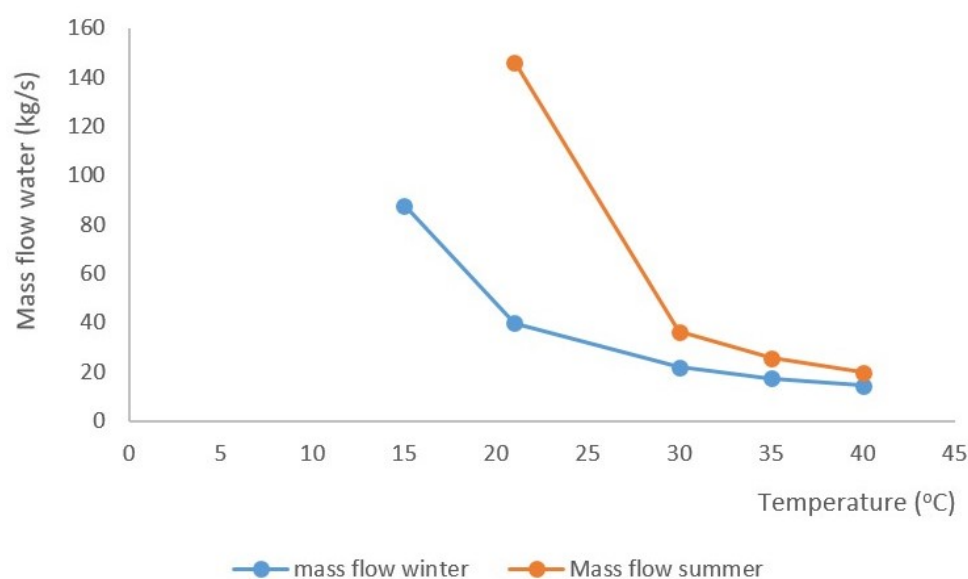


Figure 8. Water mass flow vs. temperature.

5.4.2. Energy and Financial Balance

Table 4 highlights the economic savings due to having a thermal heat recovery system for the reference temperatures from Table 3.

Table 4. Economic savings of the thermal heat recovery system.

Description	Symbol	Value	Units
Mass flow of water to evaporate	\dot{m}_w	0.463	kg/s
Initial temperature of the bagasse water	$T_{i(bw)}$	20	°C
High heating value of olive bagasse	HHV	22,860.00	kJ/kg
Heat transferred to water bagasse	\dot{Q}_t (30 °C) ^α	19.39	kW
	\dot{Q}_t (35 °C) ^β	29.07	kW
	\dot{Q}_t (40 °C) ^γ	38.76	kW
Price of olive bagasse	—	0.07	€/kg
Savings	—	1845.94 ^α	€/year
	—	2807.20 ^β	€/year
	—	3742.93 ^γ	€/year

The damage that the industrial condensing systems provokes in water bodies is always present, and this is significant concerning having control of the discharge process to contain the damage to the smallest possible amount [26], even when recommended discharge

values exist. The fines due to thermal pollution amount to around €250,000/year [27], and the economic saving due to the heat recovered is minimal also when it is not possible to reduce temperature to the recommended values. The negative impact in the river, including fines compared with the benefit of having a thermal heat recovery system, is the turning point to proceed with a heat recovery system. Independent of that decision, the internal channels must be built to improve the heat transfer rate and avoid hexane losses due to an inefficient heat exchange system. The water flows compliance with discharge values without a thermal heat recovery is 146.37 kg/s and 87.82 kg/s, respectively, for summer and winter, leading to higher pumping costs

5.5. Future Steps and Open Questions

This singular refinery is complex due to many unconventional processes, and the interaction with the environment increases the complexity even further. However, it is possible to unveil, with a heat exchange linear model, which actions are more consequential both for improving the heat exchange capacity and for solving the thermal pollution problem. One can improve heat exchange in quantity and type, but that will demand extra pumping power that an extra photovoltaic power boost may provide. A clear conclusion is that the heat recovery system will not solve the thermal pollution definitively. There are two possible solutions that will be studied in the future: Shading the 100 m return channel with local trees to avoid the solar incidence and slowing and altering the effluent return angle to the river.

6. Conclusions

In the north of Portugal, small and scattered producers extract olive oil via traditional mechanical methods. The natural olive oil bagasse from these processes produces a by-product that feeds larger regional CEF that, after processing, further extracts more olive oil and produces biomass fuel. This CEF is critical in this sector because it transforms what was initially a waste into a by-product, easing waste treatment and disposal from the smaller producers. One presents a model that evaluates a CEF olive-oil extraction factory's heat recovery process for different seasons in this work. It also identifies solutions that deliver proper heat recovery and help mitigate thermal pollution in mountainous north Portugal's Tua river.

The first measure is to alter the cooling pond layout to increase the flow's turbulence, guaranteeing a better heat exchange rate in the hexane condensation process. The construction of internal channels will enable such an increase in turbulence; however, this measure requires increasing pumping costs. A dedicated photovoltaic pumping system will compensate for this rise in pumping needs.

Developing the heat recovery to the internal processing of the CEF, namely for further drying the bagasse in 10%, is not enough to reduce the discharge temperature and correct the river's thermal pollution situation. Besides, from a financial perspective, the implementation of a thermal heat recovery system will yield annual savings of €1845.94, which only covers 0.7% of the annual fines charged by the Portuguese authorities to the CEF.

The most crucial conclusion extracted from the model is that the heat recovery process will not solve the CEF's thermal pollution. The water discharged temperatures for winter and summer are 15 °C and 9 °C above the recommended values. Besides improving the hexane condensation equipment, complementary actions are needed in the water discharge channel's layout to achieve the recommended temperature before returning to the river.

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